Initial results from phased ICRF operations on Alcator C-Mod

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The ICRF system in Alcator C-Mod offers unique opportunities to investigate technological and physics issues related to high power phased operations

1. Load Tolerant matching

Evaluate the conjugate tee approach for load tolerant matching and its compatibility with flexible phased operations

2. Current drive in the mode conversion regime

Investigate the physics of mode conversion current drive, in particular the role of the Ion Cyclotron Wave.

3. Fast particles effects

High power operations allows to investigate effects related to the energetic ion population: Alfven modes, sawtooth stabilization and destabilization…
Overview of the ICRF system in C-Mod

<table>
<thead>
<tr>
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<th>Thru 2006</th>
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<tbody>
<tr>
<td>D &amp; E-port</td>
<td>J-port</td>
</tr>
<tr>
<td>Frequency</td>
<td>~ 80 MHz</td>
</tr>
<tr>
<td></td>
<td>40-80 MHz</td>
</tr>
<tr>
<td>Power</td>
<td>2 x 2 MW</td>
</tr>
<tr>
<td></td>
<td>4 MW</td>
</tr>
<tr>
<td>Antenna</td>
<td>2 x 2 Strap</td>
</tr>
<tr>
<td></td>
<td>4 Strap</td>
</tr>
<tr>
<td>Phase</td>
<td>fixed</td>
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<tr>
<td></td>
<td>variable</td>
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</tbody>
</table>
Recent improvements in the antennas and transmission line system have improved power handling and allow flexible high power operations.

5 MW has been delivered to the plasma for 600ms with minimum impurity and density production.

- D and E-port antennas routinely achieve 1.5 MW each (10 MW/m²).
- J-port antenna achieve 3 MW (11 MW/m²) with variable phasing.

See Schilling et al., this conference P2-167.
In L-mode (limited) discharge, 2.7 MW is coupled for ~0.4 sec.

- H cyclotron resonance is:
  - ~0.67 m at 80 MHz
  - ~0.69 m at 78 MHz
- Magnetic axis is ~0.68 m

J-port heating efficiency appears similar to D and E-port antennas.

- Stored energy is response is ~ identical.
- Central electron temperature and neutron rate are similar.

Impurity and density production are similar.

- Density evolution is the same.
- Radiated power, average $Z_{\text{eff}}$ and $D_\alpha$ traces are nearly identical.
Phased operations: H-mode threshold

Power ramp to 2 MW discharges to compare H-mode threshold
- Single Null Upper configuration
- -90° phasing for J antenna

L to H transition occurs at ~ identical input power from J-port and from D and E-port antennas.
- Suggest heating efficiency is similar.
- Density and edge temperature evolution are similar

• Performance is independent of phase
• Plasma response is similar to that of the two straps antennas
1. Load tolerant matching

- Evaluated the conjugate tee configuration in plasma conditions
- Strong current imbalance between the straps was observed
- Load tolerant behavior not readily obtained with strong coupling between straps
Conjugate tee approach and load tolerant matching

Investigated the conjugate tee approach for load tolerant matching

For a wide range of loading conditions at the antenna ports \((g+jb)\), the VSWR and reflection coefficients are maintained low. ⇒ load tolerance or resilience to loading variations, could allow flexible high power operations in both L and H-mode and in ELMy plasmas.

Calculated Voltage Standing Wave Ratio (VSWR) with different stub lengths (3 curves)

Initial conductance \((g)\) normalized to \(Z_0\)

The Smith chart corresponds to the initial impedance \(g+jb\)
Evaluated the system in plasma conditions

Observed strong current imbalance between the straps

• Current ratio can be up to 2
• No degradation of heating efficiency or increased impurity production was observed.

The currents and forward power for each straps (1-2-3-4) are strongly affected when changing the stubs lengths.
Current imbalance is predicted by transmission line models
Due to changes in the inductive loading
Intrinsic to the configuration

With strong strap-to-strap coupling, the loading impedance is affected
Compact antenna design in C-Mod ⇒ strong coupling between straps

For E-antenna
• up-down coupling (same strap) : -7dB
• adjacent straps : -20dB

Bottom figure shows how the loading impedance at the antenna ports changes as the stub lengths are varied

As a result of these two effects, load tolerant matching was not obtained on E-antenna
Used transmission line model to evaluate the approach for J-antenna

Only two non-adjacent straps are powered. The other two straps are not powered but taken into account.

Reference case, symmetric stub lengths. This shows typical load variations as seen by the generator.

Conjugate tee system without strap-to-strap coupling: resilience to loading variations is obtained.

Conjugate tee system with strap-to-strap coupling: the load tolerant properties are lost.

Level of coupling between straps for J-port: adjacent straps: \(-8.5\) dB non-adjacent: \(-20\) dB / \(-32\) dB

- Load tolerant matching using non-adjacent straps in a strongly coupled four-strap array is **not readily obtained**
- Strong current imbalance is also seen ⇒ **phasing control is lost**, compatibility with flexible phased operations is not guaranteed
Model for J-port antenna
2. Mode conversion current drive

- Used TORIC to identify scenario with high MCCD
- Wave propagation and absorption can affect the current drive efficiency significantly
- High power phased operations and unique set of diagnostics (PCI, MSE…) with allow detailed comparison between theory and experiments
In multi-species plasma, fast wave dispersion relation indicates possible mode conversion from fast wave to ion Bernstein (IBW) or ion cyclotron waves (ICW) including D-T plasmas.

The IBW and ICW can transfer momentum to electrons by Landau damping.

⇒ current drive with asymmetric $k_\parallel$ launched spectrum.

- Narrow deposition profile, can change current profile locally
- Current can be driven on-axis

Cold plasma, fast wave dispersion relation:

$$n_\perp^2 = \frac{(n_\parallel^2 - R)(n_\parallel^2 - L)}{S - n_\parallel^2}$$

R, L and S are Stix notation

Dispersion relation in the MC region
Performing series of L-mode, D(3He) discharges at 8 T to investigate MCCD:

- Power absorbed by electrons is ~0.3 MW, ~20% of total power.
- Simulation suggests RF driven current is ~10 kA.

With the deposition peaked near the sawtooth inversion radius, sawtooth period increases with Ctr-CD phasing (15ms) and decreases with Co-CD phasing (5ms).

For Ctr-CD phasing, the sawtooth period increases for deposition near the q=1 surface but unchanged with the deposition peaked away from the q=1 surface.

This suggests that driven current changes the shear dq/dr locally at the q=1 surface ⇒ stabilize or destabilize m=1 internal kink modes.
**Used TORIC to investigate MCCD physics**

TORIC is a 2D full-wave finite Larmor radius code, includes dispersion relation of IBW, ICW and FW


- Competition between mode conversion and other absorption processes
- Localized deposition
- $k_{\parallel}$ up-shift and down-shift of ICW
- Resolves short-wavelength IBW and ICW
- Parallel version with EFIT equilibrium

**Current drive calculations use Ehst-Karney parameterization**

**Total current driven by IBW is small**

IBW can drive current locally on the HFS
Identified scenarios with high MCCCD

Modeled discharge:
- $BT = 5.4\, T$
- $I_p = 0.8\, \text{MA},$
- $n_{e0} = 1.4 \times 10^{20}\, \text{m}^{-3},$
- $T_{e0} = 5\, \text{keV}$
- 65% D, 15% 3He, 5% H
- J-port @ 50 MHz (MCCD)
- D and E-port @ 80 MHz (Heating)

**Driven current density equals ohmic $j(r)$ locally**

RF power: 3 MW
Total: 96 kA
Effect of mode conversion to the ICW

In addition to IBW MC, significant power can be mode-converted to the ICW for off-axis cases

• ICW propagate towards the low field side, where magnetic trapping is higher and reduces the CD efficiency

• Asymmetry due to the $k_{||}$ upshift

• Deposition location depends on focusing of the FW

Can have a strong effect on the MCCD efficiency
Unique conditions to explore MCCD

Compared to 8T experiments, operations at 5.4 T and 50 MHz from J-port in the identified D(^3)He,H) are more flexible and will allow a detailed comparison between modeling and experimental results from:

- **Phase-contrast imaging (PCI)**
  A unique diagnostic to detect ICRF waves, recently upgraded from 12 to 32 channels and higher digitizing rate (10 MHz)

  Waves with different k-vector have been measured with PCI in initial experiments at 50 MHz. The measured wavenumbers are compatible the IBW and ICW spatial dispersion relation. (Figure on the right)

- **High resolution ECE Te profiles**
  Power deposition profiles on electrons (MCEH), from break-in-slope analysis

- **I_p, loop voltage, EFIT, and Motional Stark Effect (MSE) measurements**
  To evaluate the driven current and its radial localization
3. Fast particles effects

- Effects related to energetic ion population are induced with the C-Mod ICRF system
- Alfvén modes driven by minority ion population
- First observation of monster sawteeth in C-Mod
- Sawtooth period is affected by the antenna phasing for on-axis deposition at lower currents
Alfvén modes driven by minority ion population

- Observed multiple modes post sawtooth crash, apparently suppressed later by MHD mode.
- Evidence of the presence of an energetic ion population

See Snipes et al., this conference P2-167
First monster sawtooth in C-Mod

Monster sawteeth obtained in C-Mod for the first time

\[ B_T = 5.2 \text{ T} \quad I_p = 800 \text{ kA} \]

D(H) plasmas with H/D \( \leq 5 \% \)

J-port @ 78 MHz : 2.0 MW [Heating]

D,E-port @ 80 MHz : 1.5 MW each

⇒ On-axis minority heating

*Monster sawteeth up to 80 ms long.*

Can be explained by fast particles stabilization mechanisms


Similar effects have been observed on JET and TFTR, etc…

*Heidbrink94 : Nucl. Fusion 34 (1994) 535*
Sawtooth period for on-axis deposition

\[ B_t = 5.2 \, \text{T} \quad I_p = 0.8 \, \text{MA} \quad \text{L-mode} \]

The sawtooth period is affected by the antenna phasing for on-axis deposition.
Conclusions

Using a conjugate tee configuration in plasma conditions,
• Strong current imbalance between the straps was observed and shown to be intrinsic to configuration;
• Impurity and density production was unaffected by current imbalance; and
• Load tolerant behavior is not readily obtained with strong coupling between straps.

Identify a scenario with high MCCD using TORIC
• Details of the mode conversion significantly affect the current drive efficiency.

Observation of fast ion effects with high power phased antenna operation.
• First observation of monster sawteeth in C-Mod.
• With on-axis deposition, the sawtooth period is dependent on antenna phase.